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WELDING PROCEDURE AND EVALUATION OF A HEAVY SECTION 2.25 Cr - 1 Mo STEEL WELDMENT

by

R.F. Hoare, M.W. Letts, R.V. Narraway and J.T.McGrath

ABSTRACT

A heavy section plate, 140 mm thick, of 2.25 Cr-1 Mo steel was joined using a multipass submerged arc welding process. A welding procedure was developed in which the preheat, interpass and post weld temperatures were established to prevent hydrogen cracking in the weld metal.

The as-deposited weld metal was found to have a level of notch toughness below that acceptable for application in pressure vessels for energy conversion processes. A stress relief heat treatment of 690°C for 6 h raised the weld metal toughness to meet most pressure vessel code specifications. The improvement in weld metal toughness, resulting from stress relieving, was probably caused by the development of non-coherent carbide precipitates and a decrease in dislocation density. Stress relieving resulted in an improvement in notch toughness in the heat affected zone and base metal.

INTRODUCTION

The fabrication of heavy section pressure vessels for new energy conversion processes requires the joining of Cr/Mo steels in thicknesses greater than 125 mm. Although the requirements for improved productivity and savings of consumables dictate the development of narrow gap type processes (1), the avoidance of welding related defects such as hydrogen cracking (2) and the attainment of acceptable levels of notch toughness in the weld metal and heat affected zone regions share equal importance.

The work presented in this report outlines (a) welding procedures for the avoidance of hydrogen cracking and (b) the evaluation of notch toughness properties of the weld metal and heat affected zone regions in a weldment prepared in 2.25 Cr-1 Mo steel plate 140 mm in thickness.

The work on heavy section welding is part of the Pressure Vessels Project whose primary objective is the development of fabrication technology for heavy section pressure vessels.

EXPERIMENTAL PROCEDURE

Welding

The weldment was prepared in 140 mm thick plate of 2.25 Cr-1 Mo steel using a multipass submerged arc welding process. An off set "K" joint preparation, shown in Fig. 1, was used. The submerged arc weld was deposited with Page AS 521 wire and Linde 0091 flux. The wire, base metal and weld metal compositions are included in Table 1. To avoid hydrogen cracking in the weld metal (2), the plates were preheated to 210°C. The initial three root passes were deposited with manual metal arc welding using E 7018 low hydrogen electrodes. Four passes were then deposited with single wire submerged arc welding with an energy input of 2.6 KJ/mm. The weldment was turned over and the bottom of the root region was ground to sound metal. Following grinding, four passes were deposited on the bottom side of the weld using single wire submerged arc welding. As summarized in Table 1 of Appendix 1 and illustrated in Fig. 2, welding was alternated between each side to control distortion. After each pass, the interpass temperature was maintained at 245°C for approximately 15 min to ensure rapid diffusion of hydrogen from the weld area. The temperature of the weldment was checked with Temple stick crayons.

The filling passes of the weld (beads 50 -95) were deposited with 2 wire tandem submerged arc welding at an energy input of approximately 4.2 KJ/mm.

The welding was done over a 48 h period. At the completion of each welding sequence the weldment was heated to 290°C for 40 min, covered with insulation, and allowed to slow cool. As indicated previously, the weldment was preheated to 210°C before welding was resumed.

The calculation of the cooling rate of the weldment was based upon the heat input, preheat temperature and the thickness of the plate. The detailed calculations are contained in Appendix 2. The results of these calculations indicated that a bainitic microstructure should form in the as deposited weld metal and heat affected zone regions of the weldment.

Notch Toughness Testing

Charpy impact energy vs. temperature curves were established for the base metal, heat affected zone and weld metal regions. In accordance with ASME section 8 code requirements, the Charpy bars from the weld and heat affected zone were machined from the region midway between the centre of the weld and the surface (Fig. 3). The specimens had their longitudinal axis perpendicular to the direction of welding. All specimens were notched through the thickness.

Specimens were tested in the as welded and stress relieved conditions. Stress relieving of the Charpy specimens was done at 690°C for 6 h in an argon atmosphere, followed by furnace cooling.

Hardness measurements of the Charpy specimens were taken in the as welded and stress relieved conditions.

Metallography

The structures of all regions of the weldment were recorded by optical microscopy using standard metallographic techniques.

Vertical and horizontal sections of the weld were examined macroscopically, supplemented by magnetic particle inspection, to determine whether any cracks had formed as a result of hydrogen embrittlement.

RESULTS

Mechanical Properties

The results of the Charpy impact tests on the weld metal, heat affected zone and base metal of the 2.25 Cr-1 Mo weldment are listed in Tables 2-4. The plot of impact energy vs. temperature in Fig. 4 indicates that the weld metal had low notch toughness, i.e., 13 J maximum, in the as welded condition. However, a significant improvement in fracture resistance was found after stress relieving of the weld.

The notch toughness of the base metal and heat affected zone in the as welded and stress relieved conditions are shown in Figs. 5 and 6. Both regions had significantly higher toughness than the weld metal in the as welded condition. Stress relieving generally increased the toughness of the heat affected zone, but improved the toughness of the base metal only at test temperatures $\geq$10°C.

The weldment hardness measurements are summarized in Table 3. The decrease in hardness brought about by stress relieving, was greater in the weld metal. The hardness changes in the weld metal due to stress relieving as well as those in the base metal and heat affected zone parallel the observed changes in notch toughness.

Microstructure

The microstructure of the 2.25 Cr-1 Mo base metal is shown in Fig. 7 in the as received condition and after stress relieving following welding. The base metal is composed of a mixture of about 30% ferrite and 70% bainite. The bainite contains irregular laths of ferrite separated by regions with fine precipitate, i.e., alloy carbides. Following the stress relieving treatment, the basic grain structure of the bainite does not change. The fine precipitates are more prominent indicating growth during stress relief.

The structure of the as deposited weld metal was 100% bainite as shown in Fig. 8. As in the case of the base metal no change in overall grain morphology of the bainite was observed after stress relieving. It was difficult to determine whether the fine precipitates in the bainite had grown as a result of stress relieving. These more subtle changes would have to be studied using electron microscopy.

The structure of the coarse grained region of the heat affected zone was completely bainitic and identical to the weld metal.

Examination of both horizontal and vertical sections of the weld metal revealed no indication of cracks. In other studies (2), when hydrogen induced cracking occurred in 2.25 Cr-1 Mo weld metal, cracks were observed in the vertical sections of the weld metal running transverse to the welding direction.

DISCUSSION

Avoidance of Hydrogen Cracking

In heavy section pressure vessels, when materials with thicknesses ranging from 200 ~ 300 mm are being joined by the submerged arc welding process, the combination of high residual stress and a high concentration of hydrogen can result in hydrogen induced cracking in the weld metal. Japanese workers have investigated the factors effecting hydrogen cracking and have suggested procedures for avoiding cracking in heavy section butt weldments of 2.25 Cr-1 Mo steel (2). The procedures employed in the present program were modeled after the recommendations of the Japanese program.

Although measurements of residual stress and the concentration of hydrogen were not done in this project it is appropriate to describe the role of these two factors in the initiation of hydrogen cracking in the weld metal of 2.25 Cr-1 Mo steel. It has been shown by Takahashi and Iwai that the residual stress that develops in the thick section weld has its largest tensile component in the direction parallel to the longitudinal axis of the weld (2). The magnitude of the stress varies through the section, with the maximum value at about 10-20 mm below the top surface of the weld. It was further shown that this maximum level of residual stress, i.e., 636 MPa, essentially becomes constant for plate thicknesses $\geq$50 mm.

Measurements of diffusable hydrogen through the weld thickness have indicated that the hydrogen concentration reaches its maximum value about 10 mm below the top surface and decreases with increased depth (2). Furthermore, the highest concentration of diffusable hydrogen increases with an increase in plate thickness. The increase in cooling rate with the increase in plate thickness accounts for the higher levels of hydrogen.

Thus the combination of tensile residual stress and diffusable hydrogen lead to cracks initiating in the region below the surface where both factors have their highest values. Once initiated, the cracks have the potential to propagate through the thickness of the weld.

The method of preventing the formation of cracking in 2.25 Cr-1 Mo steel weld metal is to reduce the level of diffusable hydrogen in the weld. This can be accomplished through control of the preheat, interpass and post weld temperatures. These heat treatments, in effect, slow down the rate of cooling of the weldment and accelerate the removal of hydrogen by diffusion. In the present program, weld metal cracking was avoided by using a preheat temperature of 210°C, an interpass temperature of 245°C, and a post weld temperature of 290°C maintained for 40 min. This procedure was in agreement with that of Takahashi and Iwai (2). The graph in Fig. 9 from the work of Takahashi and Iwai shows the effect on preheat and interpass temperatures in preventing cracks in 2.25 Cr-1 Mo weldments of various thicknesses.

Notch Toughness Properties

The notch toughness of the as deposited 2.25 Cr-1 Mo weld metal was much below the required level of 55 joules at 10°C usually specified for heavy wall pressure vessels for energy conversion processes. The stress relieving heat treatment of 690°C for 6 h resulted in a significant improvement in notch toughness to 63 J at 10°C. The notch toughness of weld metal can be related to microstructure. It is well known, particularly in weld metals of microalloy steels, that a high percentage of coarse proeutectoid ferrite or upper bainite can result in a low resistance to brittle fracture (3).

In the present investigation, the as deposited weld metal microstructure was mainly bainitic consisting of an irregular shaped lath structure with regions of fine precipitates between the ferrite laths (Fig. 8). This structure is in agreement with that predicted from the weld cooling rates and the CCT diagram as shown in Appendix 2. Following the stress relief heat treatment there was no observable change in the bainite grain morphology, although the notch toughness increased significantly. Thus the assumption is that the improvement in weld metal toughness with stress relief treatment is related to the precipitation of second phase particles in the weld metal.

The work of Swift documents the role of carbide precipitation in determining the level of notch toughness in 2.25 Cr-1 Mo weld metal (4). Swift's results indicated low toughness, i.e., $\leq$34 J, for as deposited weld metal and after heat treatment at temperatures $\leq$480°C. An improvement in toughness, similar in magnitude to that found in the present work, was found only after heat treatment at temperatures in the range of 650° to 700°C. Using transmission electron microscopy, Swift attributed the poor toughness in the as deposited and low temperature heat treated weld metals to a high dislocation density and the presence of non uniform microstructure associated with fine epsilon carbide and iron-molybdenum carbides. After stress relieving at higher temperatures, $\geq$650°C, non coherent carbide precipitates and a well defined dislocation cell structure were formed, resulting in improved toughness. In order to verify if similar precipitation phenomena occurred in the weld metal during the present project, an extensive study using electron microscopy would have to be undertaken.

The change in notch toughness in the heat affected zone, as a result of the stress relief treatment, was not as large as that exhibited in the weld metal. It can be assumed that stress relieving developed non coherent carbide particles in the bainite structure of the heat affected zone resulting in an improvement in notch toughness.

CONCLUSIONS

1. A welding procedure was developed in which the preheat, interpass and post weld temperatures were established to prevent hydrogen cracking in a multipass submerged arc weld prepared in a heavy section plate of 2.25 Cr - 1 Mo steel.
2. The notch toughness of the weld metal, heat affected zone and base metal exceeded the required level of 55 J at 10°C following a stress relief heat treatment of 6 h at 690°C.
3. The improvement in notch toughness in weld metal, resulting from stress relieving was probably caused by the development of non-coherent carbide precipitates and a decrease in dislocation density.

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2. E. Takahashi and K. Iwai, Trans Jap Weld Soc 10, 1, 1979, pp. 46-57.

3. J.T. McGrath, M.G. Godden, J. Gordine and J.D. Boyd, Can Met Quart 19, 1980, pp. 99-113.

4. R.A. Swift, "A Study of the Embrittlement of 2.25 Cr-1 Mo Steel Weld Metal" Ph.D. Thesis, Drexel Univ., 1974.

Table 1. Composition of filler wire, weld metal and base metal.

Elements	Filler wire	Weld metal	Base metal
Carbon	0.12	0.10	0.13
Sulphur	0.012	0.015	0.022
Nickel	0.06	0.09	n.d.
Molybdenum	1.06	0.97	0.98
Chromium	2.64	2.36	2.33
Manganese	0.58	0.39	0.45
Silicon	0.48	0.59	0.24
Phosphorus	0.012	0.010	0.013

Table 2. Weld metal notch toughness results.

Specimen	Condition	T,°C	Impact energy Joules
Weld	as-welded	25	16
	as-welded	25	10
	as-welded	10	16
	as-welded	10	11
	as-welded	10	10
	as-welded	-18	7
	as-welded	-18	7
	as-welded	-29	4
	as-welded	-29	13
Weld	Stress relieved	25	78
	Stress relieved	25	67
	Stress relieved	10	60
	Stress relieved	10	59
	Stress relieved	10	71
	Stress relieved	-18	34
	Stress relieved	-18	35
	Stress relieved	-29	20
	Stress relieved	-29	22

Table 3. HAZ notch toughness results

Specimen	condition	T,°C	Impact energy Joules
HAZ	as-welded	25	58
	as-welded	10	36
	as-welded	10	35
	as-welded	-18	7
	as-welded	-18	45
	as-welded	-29	5
	as-welded	-29	5
HAZ	Stress relieved	25	102
	Stress relieved	10	77
	Stress relieved	10	75
	Stress relieved	-18	34
	Stress relieved	-18	54
	Stress relieved	-29	23
	Stress relieved	-29	49

Table 4. Base metal notch toughness results

Specimen	Condition	T,°C	Impact energy Joules
Base metal	as-welded	25	90
	as-welded	25	71
	as-welded	10	68
	as-welded	10	80
	as-welded	10	64
	as-welded	-18	23
	as-welded	-18	23
	as-welded	-29	7
	as-welded	-29	6
Base metal	Stress relieved	25	127
	Stress relieved	25	121
	Stress relieved	10	90
	Stress relieved	10	76
	Stress relieved	10	117
	Stress relieved	-18	25
	Stress relieved	-18	26
	Stress relieved	-29	18
	Stress relieved	-29	13

Table 5. Hardness of 2.25 Cr-1 Mo weldment

Region	As welded (VHN)	PWHT (VHN)
Weld metal	341	223
Heat affected zone	273	193
Base metal	198	173

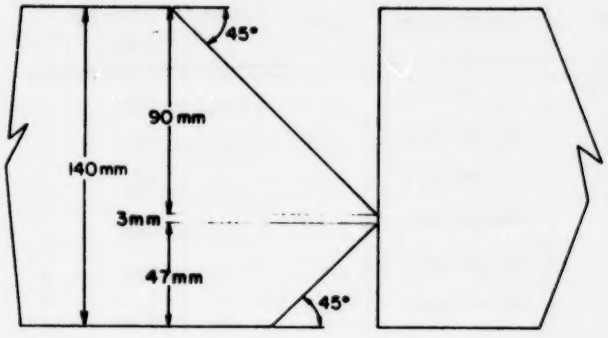

Fig. 1 - Offset 'K' joint. (neg 6131)

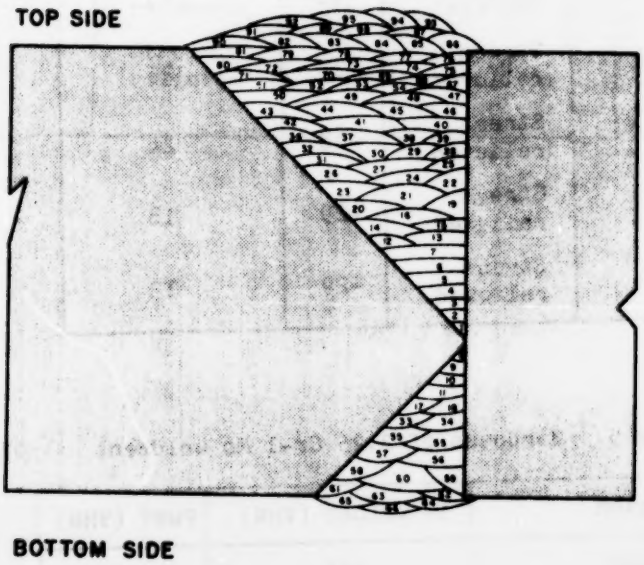

Fig. 2 - Weld pass layout. (neg 6127)

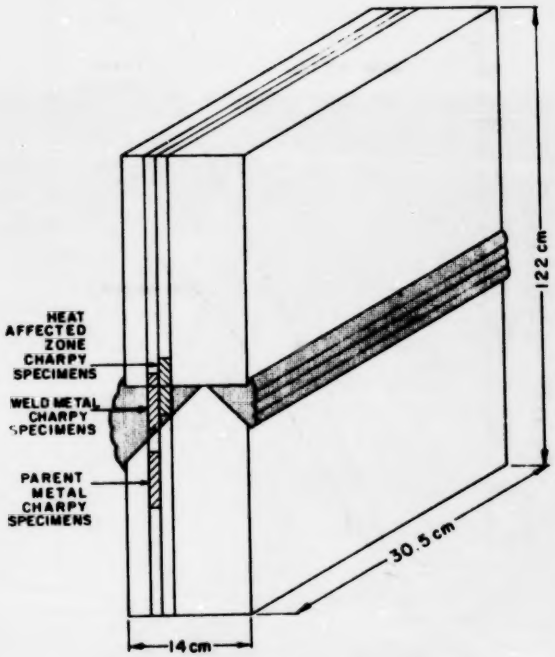

Fig. 3 - Charpy specimen location. (neg 6132)

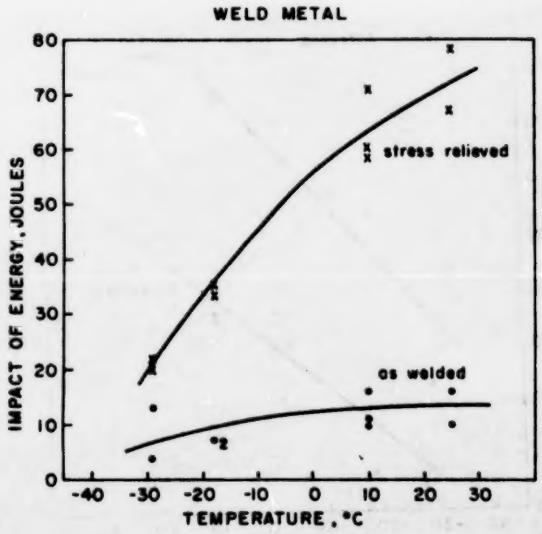

Fig. 4 - Weld metal notch toughness. (neg 6128)

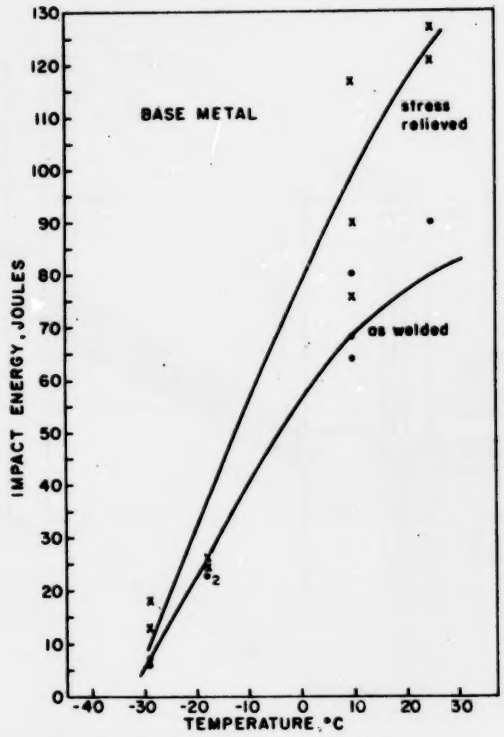

Fig. 5 - Notch toughness of base metal. (neg 6130)

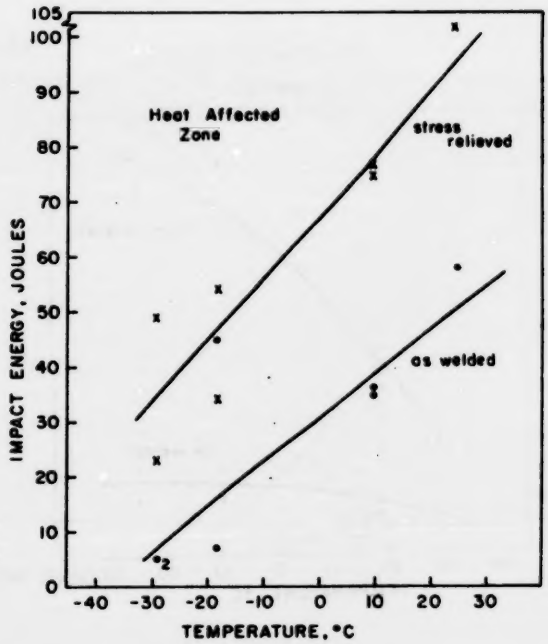

Fig. 6 - Notch toughness of H.A.Z. (neg 6133)

Fig. 7(a) - Base metal as received. X500. (neg 7024)

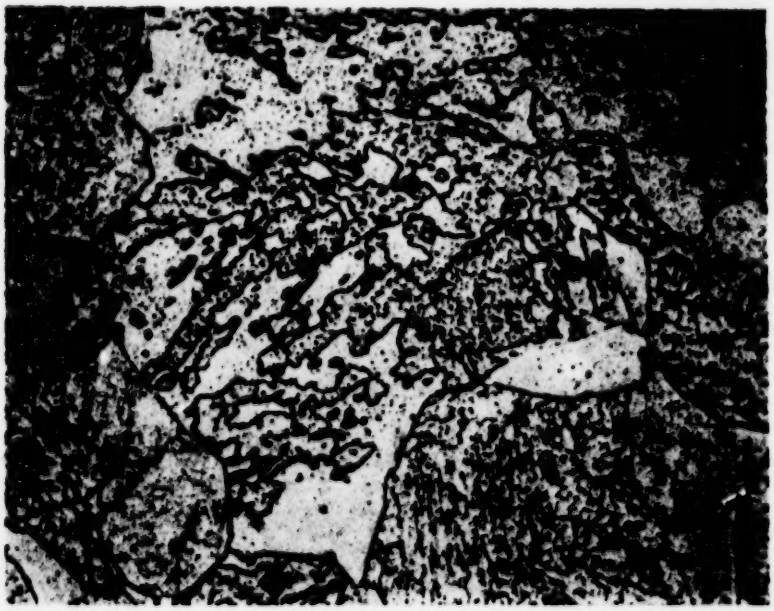

Fig. 7(b) - Base metal stress relieved. X500. (neg 7025)

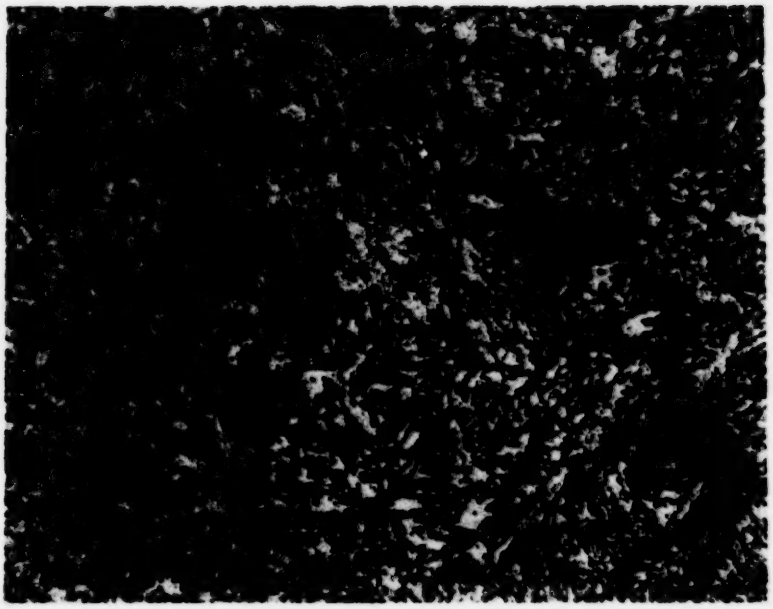

Fig. 8(a) - Weld metal as welded. X500. (neg 7026)

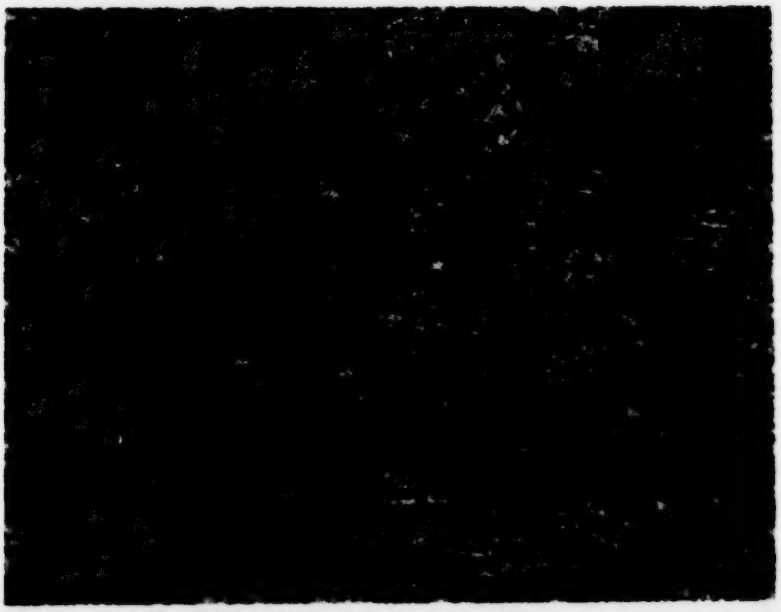

Fig. 8(b) - Weld metal stress relieved. X500. (neg 7027)

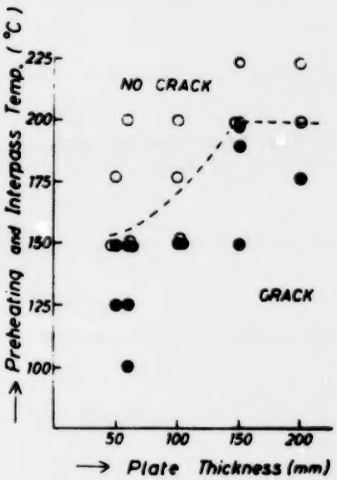

Fig. 9. Effect of preheat and interpass temp in preventing weld metal cracks (2). (neg 6129)

APPENDIX 1

Welding Consumables and Parameters

Submerged Arc (SAW)	Manual Metal Arc (SMAW)
Wire - AS 521 (Page)	Electrode - E 7018
Diameter - 5/32 inches	Diameter - 5/32 inches

Flux - Linde 0091

Preheat 210°C
Interpass 245°C

The positioning of welding wire for the tandem sub arc arrangement is shown in Fig. 1.

able 1-1. Summary of welding procedure

Weld	Pass	Lead DC+			Trail AC			
		Amps	Volts	Heat input kJ/mm	Amps	Volts	Heat input kJ/mm	Speed mm/min
Top	1-3	200	26	2.46	Stick electrode	E 7018	5/32 in.	127
Top	4-7	650	30	3.07				381
		Turned to bottom side and ground to sound metal						
Bottom	8-11	650	30	3.93				297.4
		Plate turned to top side						
Top	12-14	700	31	5.13				254
		Post weld heat treatment at 290°C for 40 min.						
Top	15-16	650	30	4.61				254
		Plate turned to bottom side						
Bottom	17-18	650	30	4.61				254
		Plate turned to top side						
Top	19-29	650	30	4.61				254
		Post weld heat treatment at 290°C for 40 min.						
Top	30-32	600	29	3.43				304
		Plate turned to bottom side						
Bottom	33-35	600	29	3.43				304
		Plate turned to top side						
Top	36-49	600	29	3.43				304
Top	50-54	700	30	1.91	800	32	2.33	660
		Plate turned over to bottom side						
Bottom	55-66	750	31	2.11	800	32	2.33	660
		Plate turned over to top side						
Top	67-75	700	30	1.91	800	32	2.33	660
Top	76-77	650	30	4.61				254
Top	78-91	700	30	1.77	800	32	2.16	711
Top	92-95	650	30	3.3				355
		Post weld heat treatment at 290°C for 40 min						

Appendix 1

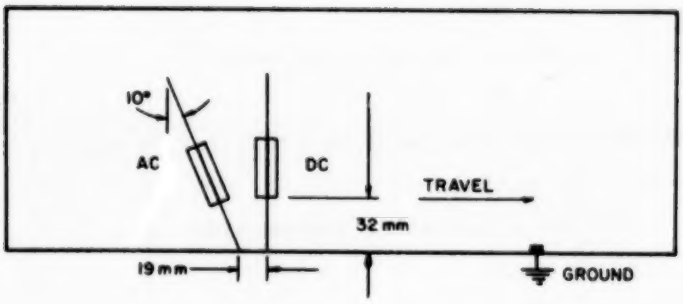

Fig. 1-1. Welding wire position. (neg 6126)

APPENDIX 2

Weld Cooling Rate Calculations

For the welding of thick plates requiring more than six passes to complete the joint, the cooling rate R is given by the following (1)

$$R = \frac{2\pi k\ Tc-To)^2}{H_{net}} \qquad (1)$$

where: R = cooling rate at a point on the weld centre line, °C/s

T_c = reference temperature, °C

T_o = preheat temperature, °C

k = thermal conductivity of the metal, J/mm.s°C

H_{net} = efficiency x heat input, J/mm

Cooling rate for SMAW welding

Passes 1 to 3

k = 0.0185 J/mm.s°C

H_{net} = 0.75 x 2400 = 1800 J/mm

T_c = 550°C (onset of transformation to bainite)

T_o = 210°C

$$R = \frac{2\pi \cdot 0.0185\ (550-210)^2}{1800}$$

= 7.46°C/s or 448°C/min

Cooling Rate for SAW Welding, Single Wire Process

Passes 4-49, 76-77, 92-95.

k = 0.0185 J/mm.s°C

H_{net} = 0.85 x 3900 = 3315 J/mm

T_c = 550°C

T_o = 210°C

$$R = \frac{2\pi \cdot 0.0185\ (550-210)^2}{3315}$$

= 7.0°C/s or 240°C/min

Cooling Rate for SAW Welding, Tandem Wire Process

Passes 50-75, 78-91

$k = 0.0185$ J/mm.s°C

$H_{net} = 0.85 \times 4236 = 3601$ J/mm

$T_c = 550$°C

$T_o = 210$°C

$$R = \frac{2\pi \cdot 0.0185\ (550-210)^2}{3601}$$

$= 3.7$°C/s or 224°C/min

In relating the cooling rates for the SMAW and SAW processes to the CCT diagram for 2.25 Cr-1 Mo steel (Fig. 1), it can be seen that a bainite microstructure should result in the weld metal and heat affected zones upon cooling of the weldment.

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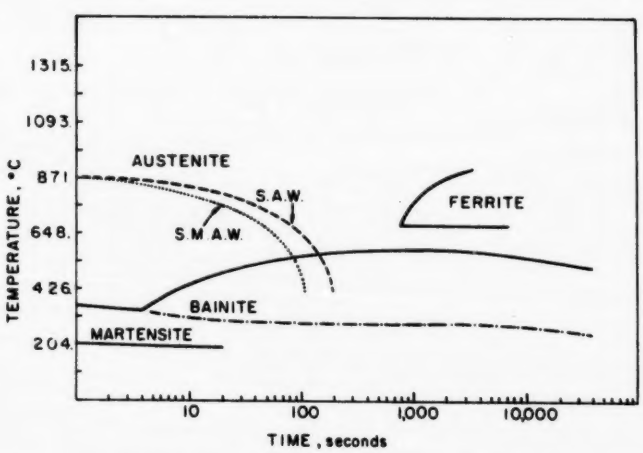
Appendix 2



CONTINUOUS-COOLING TRANSFORMATION DIAGRAM FOR 2 1/4 Cr - 1Mo STEEL (6)

Fig. 1-2. CCT diagram for 2/25 Cr-1 Mo steel (6). (neg 6125)